DP-THOT- A Calculational Tool For Bundle-Specific Decay Power Based On Actual Irradiation History [1]

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Abstract

A tool has been created for calculating the decay power of an individual fuel bundle to take account of its actual irradiation history, as tracked by the fuel management code SORO. The DP-THOT tool was developed in two phases: first as a standalone executable code for decay power calculation, which could accept as input an entirely arbitrary irradiation history; then as a module integrated with SORO auxiliary codes, which directly accesses SORO history files to retrieve the operating power history of the bundle since it first entered the core.

The methodology implemented in the standalone code is based on the ANSI/ANS-5.1-1994 formulation, which has been specifically adapted for calculating decay power in irradiated CANDU reactor fuel, by making use of fuel type specific parameters derived from WIMS lattice cell simulations for both 37 element and 28 element CANDU fuel bundle types. The approach also yields estimates of uncertainty in the calculated decay power quantities, based on the evaluated error in the decay heat correlations built-in for each fissile isotope, in combination with the estimated uncertainty in user-supplied inputs. The method was first implemented in the form of a spreadsheet, and following successful testing against decay powers estimated using the code ORIGEN-S, the algorithm was coded in FORTRAN to create an executable program. The resulting standalone code, DP-THOT, accepts an arbitrary irradiation history and provides the calculated decay power and estimated uncertainty over any user-specified range of cooling times, for either 37 element or 28 element fuel bundles.

The overall objective was to produce an integrated tool which could be used to find the decay power associated with any identified fuel bundle or channel in the core, taking into account the actual operating history of the bundles involved. The benefit is that the tool would allow a more realistic calculation of bundle and channel decay powers for outage heat sink planning. Information on the operating state of the core is calculated and recorded at regular intervals using the SORO fuel management code. To retrieve the complete history of an individual bundle requires tracking the bundle back from its current location, through all previously occupied locations in the core, to the fuelling operation at which the bundle first entered the core. Taking account of all intervening core states, including periods of shutdown or reduced reactor power, a histogram can

[1] NSS performed this work under contract from Bruce Power and Ontario Power Generation.

then be constructed representing the entire power history of the bundle up to any subsequent point during its residence within the core.

Existing capability within the SORO auxiliary suite of codes was built upon to facilitate the process of retrieving the complete irradiation history of a bundle specified in terms of its current location in the core. An interfacing routine was written to automate the process of obtaining input from the user, retrieving the bundle power history from SORO files, providing the history in the format needed for input to the decay power calculation module, executing the decay power program, and directing output back to the user. Information supplied by the user comprises identification of the reactor unit and bundles or channels which are of interest, the time and date of shutdown subsequent to which decay powers are to be calculated, as well as the associated decay time intervals. Where the decay power for complete channels is requested, the calculation is completed on a bundle by bundle basis, and then the resulting bundle decay powers are summed to yield the overall decay power for the channel. When a core scan is requested, the calculation is undertaken for every channel and bundle in the core.

The tool has been extensively tested and results from its application are presented.

INTRODUCTION

Information on power produced in irradiated fuel due to decay heat is a primary input to many safety-related calculations. The application of decay heat data can generally be classified as falling into one of three broad cooling time regimes :

i. Short term (up to approximately 1 hour) – as needed for Loss of Coolant Accident analysis

ii. Intermediate term (a few hours to a few months after shutdown) – input to the outage planning process with respect to heat sink availability, equipment recall times, waiting time for fuel channel inspection/maintenance campaigns, shipment of defective fuel for post-irradiation examination etc.

iii. Long term (months to years) – issues affecting used fuel management, both in irradiated fuel bays and dry storage containers, as well as potential long term disposal options.

The focus in this work is on the intermediate cooling time range, from a few hours decay time up to about 4 months after shutdown, encompassing the normally expected duration of unit or station outages. This is the time frame over which issues related to decay power tend to have the greatest operational impacts. In contrast to the situation at very short cooling times (seconds), where decay power is governed mainly by the immediately preceding operating power level, or the long term case (greater than a few years cooling), where decay power is primarily dependent on fuel burnup attained, the decay power of a fuel bundle in the intermediate cooling time range is a more complex function of its overall irradiation history.

Decay heat in irradiated CANDU fuel over this cooling time range may be calculated using either the ORIGEN-S isotope generation and depletion code [1], or using methods based on the ANSI/ANS-5.1 standard in its various editions [2, 3 and 4]. Most often though, a pre-calculated curve of the form P(t) / Po is applied, which expresses the decay power versus cooling time as a fraction of the operating power prior to shutdown. The principal limitation encountered in using such a single decay heat curve, whether derived using ORIGEN-S or the ANSI/ANS-5.1 standard, is not the accuracy of the underlying computational tool (which determines merely the uncertainty associated with the result for a specified set of input conditions). Rather, conservatism arises from the need to adopt stylized input assumptions that are sufficiently all-encompassing to include all potentially limiting cases.

OBJECTIVE

The objective behind the development of the DP-THOT tool was therefore to improve estimates of decay power, by performing a specific calculation for each contributing bundle to reflect its actual irradiation history, as available from fuel management codes such as SORO. The decay power can then be summed over the relevant bundles for any given channel, and further summed over channels to give the decay power for the whole core. This technique can equally well be applied to periods of reduced power operation, or situations where the unit had recently returned to power from the shutdown state, to more accurately reflect the impact on decay power of the actual operating history of the reactor.

The DP-THOT tool was developed in two phases : first as an algorithm which could be implemented as a standalone executable code for decay power calculation, capable of accepting as input an entirely arbitrary irradiation history; then as a module integrated with SORO auxiliary codes, which directly access SORO Master Files to retrieve the operating power history of a fuel bundle since it first entered the core.

METHODS FOR DECAY POWER CALCULATION

In selecting the means to be implemented for calculating the decay power of each bundle, the requirement was for a method that could reliably and efficiently provide an estimate of not only the decay power itself, but also an indication of the associated uncertainty. The method also needed to be sufficiently versatile to accommodate an irradiation history consisting of many time intervals at different power levels, including intermediate periods of shutdown or operation at low power.

The time-varying power history of any single fuel assembly can be simulated with ORIGEN-S, but for several reasons this code was not considered the optimal tool to generate decay heat results efficiently for large numbers of assemblies in an automated scheme. As an alternative, the ANSI/ANS-5.1 Standard represents a more direct means for predicting the decay heat power, and the associated uncertainty, from fission products and the major actinides following shutdown. More recent versions of the Standard [3, 4] are intended primarily for application to Light Water Reactors. However, the formulation has enough flexibility built-in to simulate, via user input options, arbitrary operating power/irradiation histories and to calculate the resultant decay heat powers for other fuel types, such as CANDU fuel, where U-235, U-238 and Pu-239 constitute the major fissile nuclides. We have previously reported the successful application of this technique to the determination of CANDU fuel decay power [5], and the method forms the basis for the decay power values and uncertainty estimates quoted in [6], adopted as a common approach within OPG and Bruce Power.

APPLICATION OF ANSI/ANS-5.1-1994 TO CANDU FUEL

Capability for CANDU decay heat prediction based on the formulation given in the ANSI/ANS-5.1 Standard had previously been implemented in the form of a spreadsheet-based method, as described in [5]. Prior to its further utilization as the algorithm to be implemented in the DP-THOT standalone code, a number of refinements were introduced into the approach by upgrading both the underlying method and input data. These improvements were first applied in updated versions of the spreadsheet method, used to carry out testing during the model development phase, and then incorporated in the executable code which performs calculations identically to the finalized version of the spreadsheet.

First, the formulation was updated from the 1979 version [3] of the ANSI/ANS-5.1 Standard to the most recent version [4] released in 1994. The primary difference in the 1994 version of the Standard is the specification of separate data for Pu-241 as a fissile isotope, in addition to that for U-235, U-238 and Pu-239. ANSI/ANS-5.1-1994 also includes revised decay heat data and uncertainties to reflect improved evaluations of experimental data and summation calculations. By themselves, these revisions to the underlying formulation give rise to barely perceptible changes in predicted decay power within the decay time range of interest for outage heat sink applications. In other words, using the same inputs, calculations based on ANSI/ANS-5.1-1994 give essentially the same results as those based on ANSI/ANS-5.1-1979.

In conjunction with this upgrade, improvement was also made to the means of generating the CANDU specific data needed as input to the ANS-5.1 formulation, namely fission rate fractions as a function of fuel burnup, and Q values for fission and neutron capture. All data needed to support the method is now taken either directly from ENDF/B-VI data sources, or derived from simulations using WIMS [7] for the appropriate CANDU lattice cell (37 element or 28 element type natural uranium fuel).

STANDALONE DP-THOT TOOL

Changes were introduced first into the upgraded spreadsheet based on ANSI/ANS-5.1-1994, the results from which were benchmarked against those from the earlier spreadsheet based on the 1979 standard, as well as directly against ORIGEN-S predictions. Relative differences in decay power between the two versions of the spreadsheet were very small, typically less than 0.3%. Over the relevant range of cooling times (a few hours to a few months), the nominal decay power result obtained using the upgraded spreadsheet method agreed with the ORIGEN-S prediction to within 2%. The associated 1 sigma uncertainty (including allowance for uncertainty in input parameters) calculated using the ANSI/ANS-5.1-1994 formalism amounts to about 4%. The updated formulation was then implemented as an executable code, written in FORTRAN, and the resulting program verified. Testing showed that, within the limits of precision associated with the computing platform, the standalone program produced identical results to those generated using the revised spreadsheet based on ANSI/ANS-5.1-1994.

INTERFACING WITH SORO AUXILIARY CODES

The overall objective was to produce an integrated tool which could be used to find the decay power associated with any identified fuel bundle or channel in the core, taking into account the actual operating history of the bundles involved. Information on the operating state of the core is calculated and recorded at regular intervals using the SORO fuel management code. To retrieve the complete history of an individual bundle requires tracking the bundle back from its current location, through all previously occupied locations in the core, to the fuelling operation at which the bundle first entered the core. Taking account of all intervening core states, including periods of shutdown or reduced reactor power, a histogram can then be constructed representing the entire power history of the bundle up to any subsequent point during its residence within the core.

Existing capability within the SORO auxiliary suite of codes was built upon to facilitate the process of retrieving the complete irradiation history of a bundle specified in terms of its current location in the core (or the bundle occupying that location at any earlier requested time). An interfacing routine was written to automate the process of obtaining input from the user, retrieving the bundle power history from SORO files, providing the history in the format needed for input to the decay power calculation module, executing the decay power program, and directing output back to the user. Information supplied by the user comprises identification of the reactor unit and bundles or channels which are of interest, the time and date of shutdown subsequent to which decay powers are to be calculated, as well as the associated decay time intervals. Where the decay power for complete channels is requested, the calculation is completed on a bundle by bundle basis, and then the resulting bundle decay powers are summed to yield the overall decay power for the channel. When a core scan is requested, the calculation is undertaken for every channel and bundle in the core.

INTEGRATED DP-THOT USER INTERFACE

The DP-THOT User Interface operates by accessing the SORO Master Files on the SUN network where SORO is installed, requiring user responses to only a few simple on-screen prompts to initiate a case. Run times are typically on the order of 5 to 10 minutes for a single bundle or channel scan, although whole core scans generally require several hours to execute.

Significant effort has been invested in making the process of retrieving bundle histories sufficiently robust to handle all fuelling shift patterns presently in use at operating Bruce Power and OPG reactors. The integrated program has been extensively tested, through both verification of the history file produced for each bundle during the tracking process, as well as cross-comparison of the resulting decay power values. Test cases have been successfully completed for individual bundles, single channels and the whole core, based on actual or assumed reactor shutdowns at all of the operational OPG and Bruce Power reactor units.

SAMPLE APPLICATION

A useful application of the DP-THOT tool is evaluation of the degree of conservatism inherent in use of the approach recommended in the OPG/BP Corporate Review of Outage Heat Sinks (CROHS) report [6] to determine bounding values of decay power, for heat sink assessment purposes. The bounding values of decay power are calculated, as a function of decay time, as the product of the tabulated CROHS value for fractional decay power P(t)/Po, inclusive of one sigma uncertainty, times the license limit bundle power or channel power, as appropriate, at the applicable reactor power level. The fractional decay power curve included in the CROHS report is based on a power history which assumes irradiation at a constant core-average power level until core-average burnup is reached. While these stylized assumptions are reasonably representative for the core as a whole, they represent conservative conditions for the most limiting high power channels and bundles, which invariably have accumulated less burnup than the core-average value.

The effects are illustrated in Figures 1 to 4, which present the conclusions for an assumed shutdown of Bruce Unit 6 occurring on 2 March 2002. Figure 1 shows the operating power history of the unit for more than 2 years beforehand. As can be seen, at the assumed shutdown date, Bruce Unit 6 had operated almost uninterrupted at its maximum licensed power level of 90% for a period of about 20 months, more than sufficient for fueling equilibrium to have been established at that power level.

Bundle decay powers calculated using the DP-THOT tool are illustrated in Figure 2. The quantity plotted is the total decay power (including 1 sigma uncertainty) expressed in Watts. The series of points superimposed at each cooling time represents the collection of results for the most limiting bundle in each of the 480 channels, so the uppermost point in the range indicates the most limiting bundle in the entire core at that particular decay time. Also shown on the same figure for each cooling time is the equivalent result obtained from application of the CROHS fractional decay power curve to the license limit bundle power at 90% FP. Again, the quantity plotted is the total decay power (including 1 sigma uncertainty) expressed in Watts. Finally, making use of the percentage scale shown along the right hand edge of the graph, the series of points shown toward the top of the plot is the relative difference between the CROHS result and the most limiting result obtained for any bundle using the DP-THOT tool.

Figure 3 presents equivalent information on decay powers evaluated for channels instead of bundles. The distribution of points plotted at each cooling time thus represents the spread in channel decay powers over 480 channels. Again the uppermost curve, which should be read using the percentage scale at the right hand side, shows the relative difference between the CROHS result and the most limiting result obtained for any channel in the core. Finally, Figure 4 shows the overall decay power evaluated for the entire Bruce Unit 6 core. The core decay power is calculated as the sum over all channel decay powers, which in turn are obtained by summing over bundle decay powers. All decay power results plotted, whether calculated using the DP-THOT tool or derived from the CROHS curve, include one sigma uncertainty allowance.

CONCLUSIONS

It is readily apparent from the example presented that for both bundles and channels, the predicted decay powers in all cases are well below the envelope defined by the CROHS decay power curve when applied to license limit power values. This conclusion has been confirmed by consistent results obtained in many different reactor units under varying shutdown conditions. This is a good demonstration of the utility of the DP-THOT tool, and indicates the extent of the improvement available in decay power estimates by using a method that accounts for the actual irradiation history of the specific fuel bundles involved.

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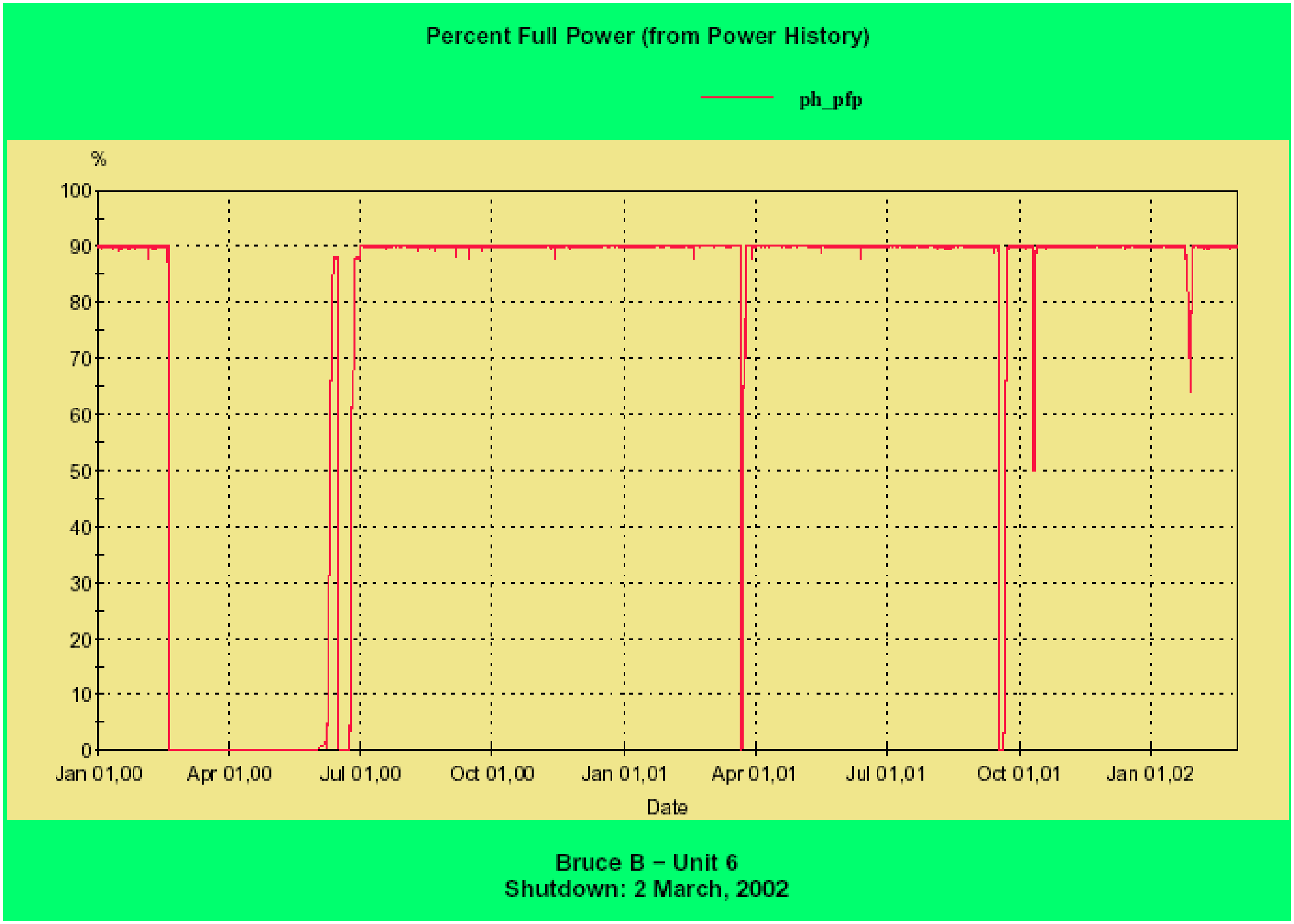
Percent Full Power (from Power History)
ph_pfp
%
100
90
80
70
60
50
40
30
20
10
0
Jan 01,00
Apr 01,00
Jul 01,00
Oct 01,00
Jan 01,01
Apr 01,01
Jul 01,01
Oct 01,01
Jan 01,02
Date
Bruce B – Unit 6
Shutdown: 2 March, 2002

Figure 1: Bruce Unit 6 Reactor Power History from January 2000 to March 2002

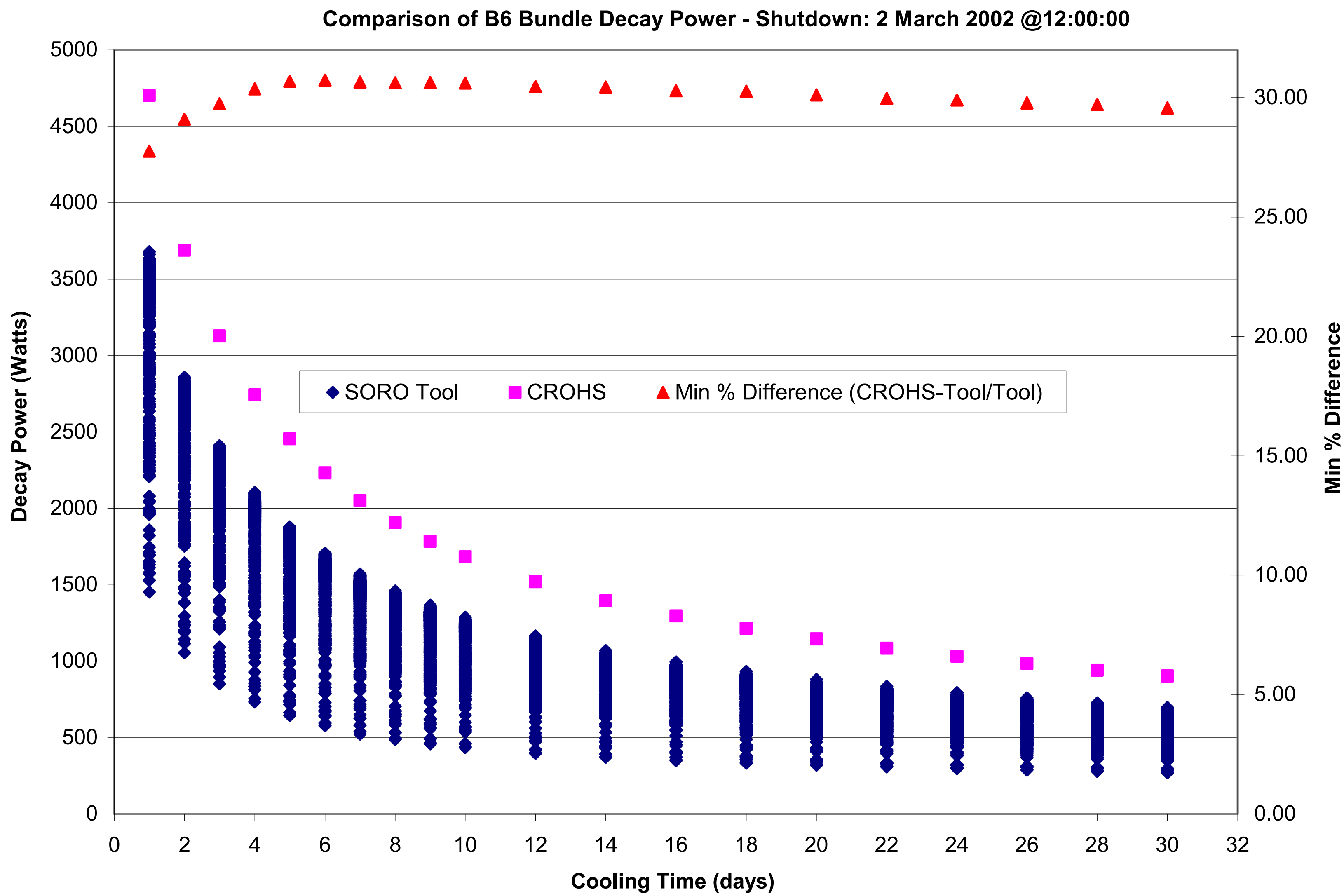

Figure 2
Comparison of Bundle Decay Power from SORO-Tool with Values Based on Data in the CROHS Report for Bruce B Unit 6 - Shutdown: 2 March 2002

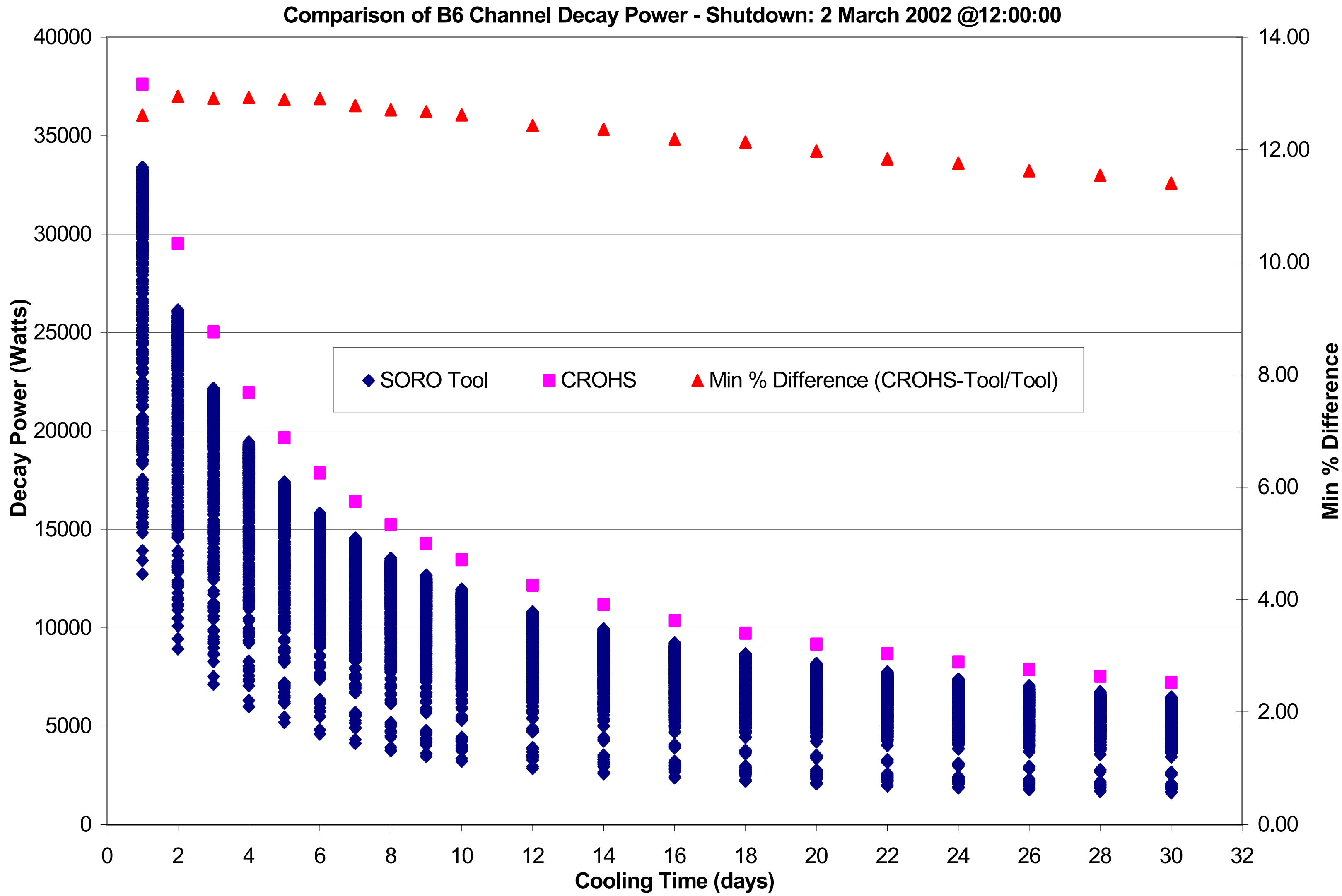

Figure 3
Comparison of Channel Decay Power from SORO-Tool with Values Based on Data in the CROHS Report for Bruce B Unit 6 - Shutdown: 2 March 2002

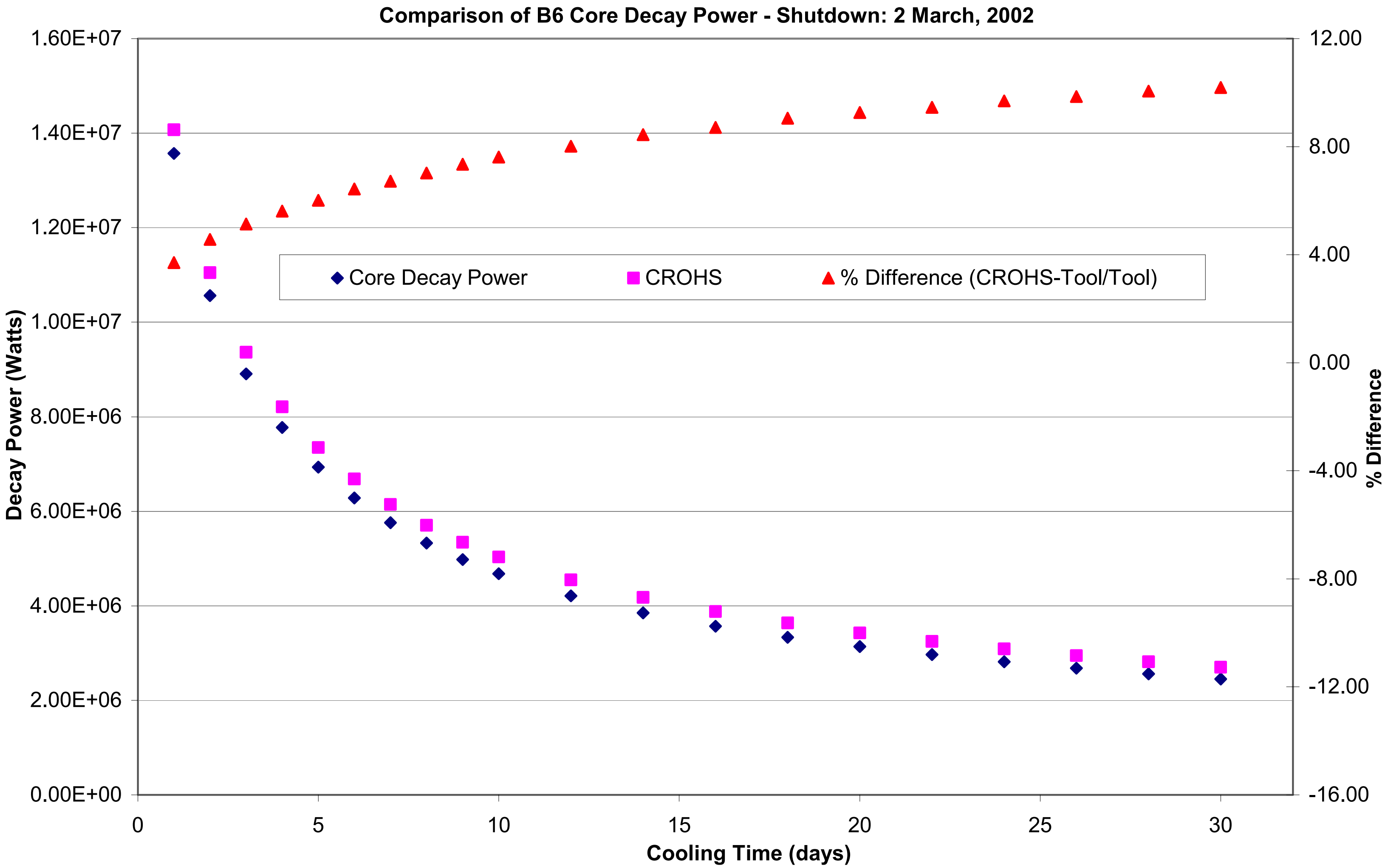

Figure 4
Comparison of Core Decay Power from SORO-Tool with Values Based on the CROHS Report for Bruce B Unit 6 - Shutdown: 2 March, 2002